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The contribution of wind-hydro pumped storage systems in meeting Turkey's electric energy demand

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ABSTRACT

Renewable energy resources have played an important role to meet increasing energy demand in the world. Among the renewable energy resources, especially, wind energy is of interest due to some advantages, such as being clean, environmental friendly etc. However, the intermittent nature of wind creates several problems to the power system operation and new approaches based on the combined use of wind power and energy storage technologies need to be developed. One of these combined systems is wind-hydro pumped storage systems. In this paper, hydropower and wind energy potential of Turkey are investigated in details. Besides, the importance and the necessity of wind-hydro pumped storage systems for Turkey are comprehensively examined and finally, the contribution of wind-hydro pumped storage systems is emphasized in meeting Turkey's electric energy demand.
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Contents

1. Introduction

Geographically, Turkey is between the old world continents of Asia, Africa, and Europe. The country is located in the northern half of the hemisphere at a point that is about halfway between the equator and the North Pole. Turkey's geographical coordinates are 36° to 42° north latitude and 26° to 45° east longitude. It has a total area of 814,578 km^2 [1,2]. Turkey's geographical location makes it a natural bridge between the energy-rich Middle East and Central Asian regions. Because of social and economic development of the country, the demand for energy, particularly for electricity, is growing rapidly. Energy is one of Turkey's most important development priorities. Rapid increase in domestic energy demand has forced Turkey to increase its dependence on foreign energy supplies [2,3].

Because of social and economic development of the country, the demand for energy and particularly for electricity is growing rapidly in Turkey. Turkey's natural energy resources are quite miscellaneous; for example, hard coal, lignite, asphalt, oil, natural gas, hydro, geothermal, wood, animal and plant wastes, solar and secondary energy resources, coke, and briquettes. These resources are produced and consumed in the country. Turkey does not own large fossil-fuel reserves. In the future, it seems that it will be very difficult to meet the anticipated demand for oil, natural gas, and even coal. On the other hand, Turkey has huge reserves of renewable energy sources [4,5]. In Turkey, where there is no

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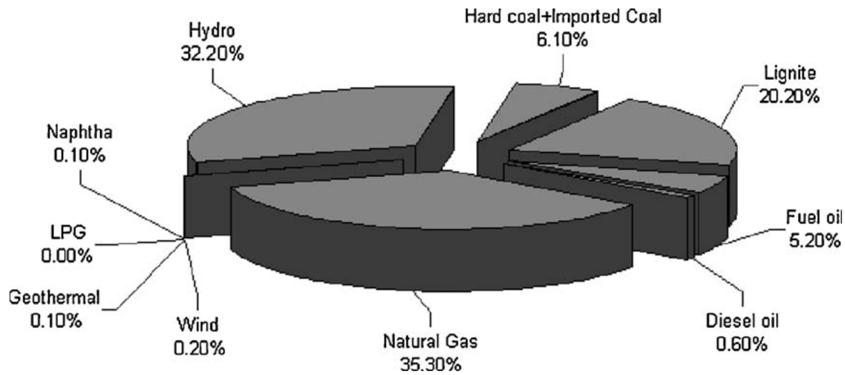

Fig. 1. Percentages of electricity generation by primary energy resources by 2007.

nuclear power, electricity is produced by TPPs, consuming coal, lignite, natural gas, fuel oil and geothermal energy; and by hydropower plants (HPPs) [5]. Turkey's main fossil energy resource is coal, which has been produced for years domestically, and its share of the country's total energy consumption is about 24%. It is used mainly for power generation, cement production, and steel manufacturing. Turkey is one of the biggest producers of lignite in the world. This comes predominantly from deposits of the Southwest and the Southeastern Afsin-Elbistan Basin, where 7339 million tonnes lignite is economically usable. The government plans to increase the coal supply from 20.1 Mtoe in 1999 to 118.4 Mtoe in 2020 [5].

Turkey's energy demand is met through thermal power plant consuming coal, gas, fuel oil and geothermal energy, wind energy and hydropower. Because Turkey does not own any nuclear power plant yet, the installation of first nuclear power plant with a capacity of 1000 MW is on the schedule as a plan of the near future. Turkey's installed generation capacity is 40,564.8 GW and electricity generation is 176299.80 GWh in year 2006. According to Turkey's Government Statistic Institute (DIE), 67.06% of Turkey's generated electricity is supplied from thermal power plants. Contribution of wind and hydro power plants are 0.2% and 32.20%, respectively. 49.00% of Turkey's electricity is generated by Electricity Generation Incorporation (EUAS), 39.70% is generated by auto-producers, and 9.5% is generated by affiliated partnerships of EUAS and 1.8% by distribution of electricity generation by primary resources by 2007 is given in Fig. 1 [6].

According to Chambers of Electrical Engineers, Turkey has 259 billion kWh energy potential, but only 35% of this potential can be used. Nowadays, Turkey's electricity generation is approximately 176 billion kWh per year and will be 400–500 billion kWh per year by year 2020. As it is seen in Fig. 1, the most important energy sources are thermal and hydro power plants. Thermal and hydro power plants' installed capacity increments are shown in Fig. 2. Power plant's installed capacities are approximately equal at the year of 1997. At the end of 2006, comparing thermal power plant installed capacity to hydro; thermal capacity is big more than twice. 35.30% of the thermal source is derived from natural gas [7].

In this paper, firstly, current status and potential of wind energy and hydropower of Turkey are investigated in details. Then, the importance and the necessity of wind-hydro pumped storage systems for Turkey are comprehensively examined and the contribution of wind-hydro pumped storage systems is emphasized in meeting Turkey's electric energy demand.

2. Current status and potential of wind power in Turkey

Recently, wind power as a potential energy has grown at an impressive rate in Turkey due to the fact that wind energy is an abundant, clean, affordable, environmentally preferable, elegant and inexhaustible energy source. Therefore, it is preferred more than the other types of renewable energy sources to produce electricity. It has been gaining importance during the last decade in Turkey [8].

Wind is one of the fastest growing energy sources, and is regarded as an important alternative to traditional power generating sources. Additionally, it is a promising energy source which can meet energy demand of Turkey in future. Total theoretically available wind potential of Turkey is estimated to be around 88,000 MW and Turkey has 160 TW h a year of wind potential, which is about twice as much as the current electricity consumption of Turkey [8]. Wind-energy-generating capacity was installed in Turkey in 2006, 2007, and in the first half of 2008, 51, 131.35 and 333.35 MW, respectively [9–11].

The values of technical wind energy potential of European countries are given in Table 1. As shown in Table 1, Turkey has the highest share in technical wind energy potential in Europe [12]. The biggest share of global wind energy capacity is held by Europe at 73%. Turkey had a share of 0.11% in Europe's installed capacity at the end of 2006. The installed capacity of Turkey's wind energy has increased from 9 MW in 1998 to 19 MW in 2001. At the first half of 2008, it has reached 333,35 MW. But the installed wind energy capacity is very small. Actually, Turkey wind energy potential is high although commercial wind energy is new [12].

Annual average wind speed and annual average wind energy potential of various regions of Turkey are shown in Table 2. The annual average wind speeds range from a low of 2.1 m/s in the East Anatolia region to a high of 3.3 m/s in the Marmara region. The most attractive regions for wind energy applications are the Marmara, the southeast Anatolian and the Aegean regions. These regions are highly suitable for wind power generation, since the wind speed exceeds 3 m/s in most of these areas [12–14].

In Turkey, electricity generation through wind energy for general use was first realized in Izmir in 1986 with a 55 kW nominal wind energy capacity. However, the utilization of wind energy in Turkey has increased since 1998 when the first wind

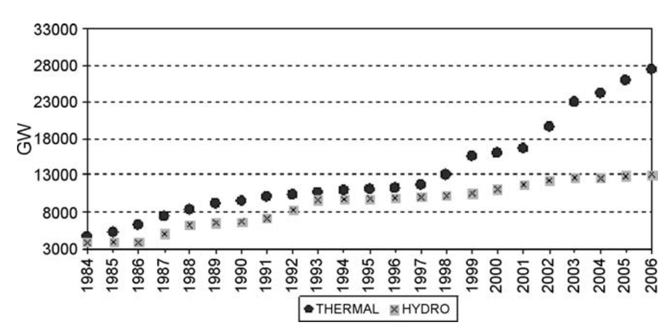

Fig. 2. Thermal and hydro power plant installed power capacity deviations.

Table 1
Technical wind energy potential of European countries.

Country	Total area (1000 km)	Technical potential	
		GW	TW/year
Austria	84	2	3
Belgium	31	2	5
Denmark	43	14	29
Finland	337	4	7
France	547	42	85
Germany	357	12	24
United Kingdom	244	57	114
Greece	132	22	44
Ireland	70	22	44
Italy	301	335	69
Luxemburg	3	0	0
Norway	324	38	76
Portugal	92	7	15
Spain	505	43	86
Turkey	781	83	166

power plant with a total capacity of 1.5 MWwas installed. Up to date, Turkey has about 200 MW wind power installed capacity in operation and about 600 MW under construction. Also, EMRA issued licenses for about 2500 MW wind power capacity and license applications for a total capacity of 77871.4 MW have been submitted to EMRA by private developers as of November 2007 [15]. Table 3 shows historical development of wind power in Turkey [16].

In Turkey, the highest monthly wind speed values are determined as 11.4–13.7 m/s in Nurdagi, 8.7–11.0 m/s in Belen, 7.2–10.3 m/s in Kocadag and 6.5–10.0 m/s in Akhisar in summer. The wind speed values are higher in summer in most of the stations. Wind speed is between 3 and 4 m/s at the northwestern corner, along the Eastern Mediterranean coast of Turkey, in the southeastern and in the northeastern of Turkey. The central Anatolian region does not provide potential wind energy locations. Turkish wind energy potential atlas (REPA) is developed by Electrical Power Resources Survey and Development Administration. Turkish wind energy potential atlas (REPA) is seen in Fig. 3.

Following items are obtained by REPA:

- Annually, seasonal, monthly, and daily mean wind speeds at 30, 50, 70 and 100 height.
- Annually, seasonal, monthly wind power densities at 50 and 100 m.
- Capacity factor at 50 m height.
- Annually wind class at 50 m height.
- Monthly temperature values at 2 and 50 m height.
- Monthly pressure values at 50 m and sea level height.

The wind energy potential which has the highest values (50–200 W/m^2) in the same parts of Turkey is obtained by REPA map [17].

Table 2
Annual average wind speed and annual average wind energy potential of various regions of Turkey.

Region	Annual average wind density (W/m^2)	Annual average wind speed (m/s)
Marmara	51.9	3.3
Southeast Anatolia	29.3	2.7
Aegean	23.5	2.6
Mediterranean	21.4	2.5
Black Sea	21.3	2.4
Central Anatolia	20.1	2.5
East Anatolia	24.0	2.5

As it is shown in Table 4, wind power plant projects are classified as three categories. These are completed wind power plants, built operate and transfer wind power plants and constructing wind power plant. Wind power installed capacity by the end of 2007 is 131.35 MW. It is expected about 677.5 MW by the end of 2009. Taking installed and planned to be installed wind based power plants into consideration, a huge amount of them placed on Aegean, Marmara and East Mediterranean regions. Among the established wind based power plants Bares A.S. has the biggest installed capacity. In addition, Mare A.S. is planning to operate a 39.20 MW installed capacity power plant in first period of 2007. At the end of first period of 2007, total installed capacity has reached 131.35 MW in Turkey. Considering new investment on based wind power plants, by the first period of 2009 total installed capacity is planned to be 677.5 MW in Turkey. Wind energy was not paid sufficient attention until Renewable Energy Law, since generated energy from wind was not guaranteed to be bought by the government. Interest to wind energy increased after renewable energy Law No. 5346. In 2005, Turkey passed the renewable energy Law No. 5346 which aims to deploy renewable energy resources usage, and exploiting ensures the government's guarantee to buy generated electric energy by private sector. Therefore, investment on power generation based on renewable energy resources such as wind, solar and geothermal has increased slightly. At present, not only the electricity sector, the whole energy sector in Turkey is in a dynamic change. According to Energy Market Regulatory Authority (EPDK) reports, new wind power plant license applications are reached to 78 GW by the end of the November 2007. Up to now, only 2 GW of the total license applications was permitted by Energy Market Regulatory Authority [12,18].

3. Current status and potential of hydropower in Turkey

Hydropower provides 2.2% of the world's total primary energy supply or 16.4% of renewable and is expected to be the fastest-growing renewable energy source in developing countries. Hydropower will continue to be an important source of electricity generation in many developing countries and is critically important for many countries; hydropower produces more than 50% of electricity for 65 countries [19–21]. Canada is the largest hydropower producer; the second largest hydropower producer is United States and follows Norway. More than 50% of the total hydropower in OECD countries is met by these three countries, namely Canada, United States and Norway. Other large hydropower producers are Japan, Sweden and France respectively. Theoretical, technically feasible, and economically feasible hydro electric potential by region in the world as well as in Turkey is presented in Table 5 [22,23].

Turkey does not have enough primary energy sources, but has a tremendous hydropower potential [24]. Nowadays, hydropower is recognized as the most important kind of renewable and sustainable energy sources. The position of hydro power plants (HPP) becomes more and more important in today's global renewable technologies. The small-scale renewable and distributed generation may be the most cost-effective way to bring electricity to remote villages that are not near transmission lines [19].

In terms of hydropower potential, with 440 TWh/year, Turkey is the second richest country after Norway in Europe. This potential can be used technically 215 TWh/year and economical potential 128 TWh/year in accordance with the predictions of General Directorate State Hydraulic Works (DSI). 35% of the economically feasible hydropower, total 45.155 GWh/year is in operation, 8% (10.129 GWh/year) is under construction and 57% (72.339 GWh/year) is being designed. Those are being designed are divided into seven categories and given in Fig. 4 as follows: 18% (23.183 GWh/

Table 3
Historical development of Wind power in Turkey [16].

Year	Production and consumption (GWh)		Installed capacity (MW)		Share of wind power in total consumption (%)	Share of wind power in installed capacity (%)
	Wind power production	Total power consumption	Wind power installed capacity	Total installed capacity		
1998	6	114,023	9	23,263	0.005	0.039
1999	21	118,485	9	26,125	0.018	0.034
2000	33	128,276	19	27,264	0.026	0.070
2001	62	126,871	19	28,332	0.049	0.067
2002	48	132,553	19	31,752	0.036	0.060
2003	61	141,151	19	35,564	0.043	0.053
2004	58	150,018	19	36,824	0.039	0.052
2005	59	160,794	21	38,820	0.037	0.054
2006	127	174,230	59	40,519	0.073	0.146
2007	?	?	161	40,755	–	0.395

Table 4
Wind power plant projects in Turkey.

Location	Company developed the project	Commissioning	Installed capacity (MW)
Completed wind power plants			
Izmir-Cesme	Alize A.S.	1998	1.50
Istanbul-Hadimköy	Sunjüt A.S.	2003	1.20
Balikesir-Bandirma	Bares A.S.	I/2006	30.00
Istanbul-Silivri	Ertürk A.S.	II/2006	0.85
İzmir-Cesme	Mare A.S.	I/2007	39.20
Manisa-Akhisar	Deniz A.S.	I/2007	10.80
Canakkale-Intepe	Anemon A.S.	I/2007	30.40
Built operate and transfer wind power plants			
Izmir-Cesme	Ares A.S.	1998	7.20
Canakkale-Bozcaada	Bores A.S.	2000	10.20
Total			131.35
Constructing wind power plant			
Canakkale-Gelibolu	Dogal A.S.	II/2007	15.20
Manisa-Sayalar	Dogal A.S.	II/2007	30.40
Hatay-Samandag	Deniz A.S.	II/2007	30.00
Istanbul-Gaziosmanpasa	Lodos A.S.	I/2008	24.00
Izmir-Aliaga	Innores A.S.	I/2008	42.50
Aydin-Çine	Sabas A.S.	I/2008	19.50
Istanbul-Çatalca	Erturk A.S.	I/2008	60.00
Canakkale	As Makinsan Temiz A.S.	II/2008	30.00
Izmir-Kemalpasa	Ak-El A.S.	II/2008	66.66
Hatay-Samandag	Ezse Ltd. Şti.	II/2008	35.00
Hatay-Samandag	Ezse Ltd. Şti.	II/2008	22.50
Balikesir-Samlı	Baki A.S.	II/2008	90.00
Bilecik	Sagap A.S.	II/2008	67.00
Balikesir-Bandirma	Bangüç A.S.	II/2008	15.00
Osmaniye-Bahce	Rotor A.S.	I/2009	130.00
Total			677.5

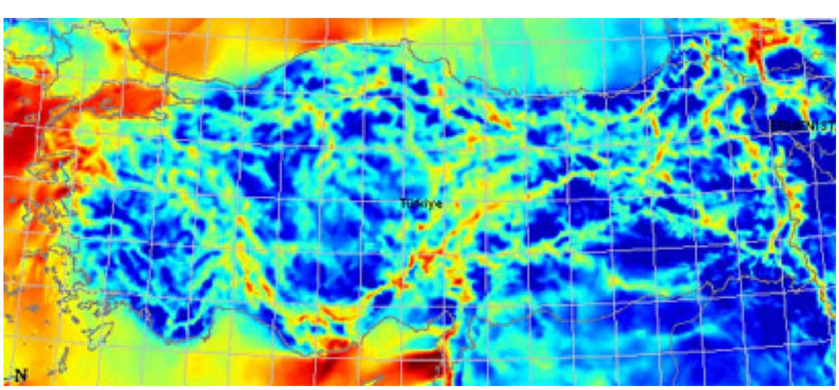

Fig. 3. Turkey wind energy potential atlas.

Table 5
Theoretical, technically and economically feasible hydro electric potential by region.

Region	Gross theoretical potential (TWh/year)	Technically feasible potential (TWh/year)	Economically feasible potential (TWh/year)	Installed hydro power capacity (GW)	Hydropower production (TWh/year)
Central and Eastern Europe	195	216	128	9.1	27
Centrally Planned Asia	6511	2159	1302	64.3	226
Former Soviet Union	3258	1235	770	146.6	498
Latin America and Caribbean	7533	2868	1199	114.1	519
Middle East and North Africa	304	171	128	9.1	27
North America	5817	1509	912	141.2	697
Pasific Asia	5520	814	142	13.5	41
Pasific OECD	1134	211	184	34.2	129
South Asia	3635	948	103	28.5	105
Sub-Saharan Africa	3583	1992	1288	65.7	225
Western Europa	3294	1822	809	16.3	48
World Total	40784	13945	6965	654.8	2581
Turkey	435	215	128	12.6	45
Turkey/world total (%)	1.07	1.54	1.84	1.92	1.74

year) with feasibility report ready, 12% (15.707 GWh/year) with preliminary report ready, 9% (11.113 GWh/year) with master plan ready, 9% (11.027 GWh/year) with final design ready, 4% (5.339 GWh/year) with feasibility report under preparation, 3% (4243 GWh/year) with final design under preparation and 1% (1.727 GWh/year) with preliminary report under preparation [25].

Water sources in Turkey are distributed into 26 basins and the total flow rate of water sources for energy production is 186 km^3/years. The biggest five basins of Turkey are Euphrates, Tigris, Eastern Black Sea, Eastern Mediterranean, Antalya respectively. Euphrates represents over 17% of the national water supply, Tigris represents over 11.5% of the national water supply, Eastern Black Sea represents 8% of the national water Supply, Eastern Mediterranean represents 6% of the national water supply, and Antalya represents 5.9% of the national water supply [24].

The construction of more than 329 hydropower plants is projected to add a total installed capacity of 19 699 MW, thus the total number of hydro plants is to bring to 483 and will be the total installed capacity of 34 592 MW by 2020 [20]. This increase includes the south-eastern Anatolia Project (GAP) which covers one-tenth of Turkey's total land area. GAP will have an installed capacity of 7460 MW [25–27]. Following the succession of this project, 1.7 million hectares of land will be irrigated and the ratio of irrigated land to the total GAP area will increase from 2.9% to 22.8% while that for rain-fed agriculture will decrease from 34.3% to 7%. On the other hand, 27 billion kWh of electricity will be generated annually over an established capacity of 7460 MW. The area to be irrigated accounts for 19% of all the economically irrigable area in Turkey (8.5 million hectares), and the annual electricity generated

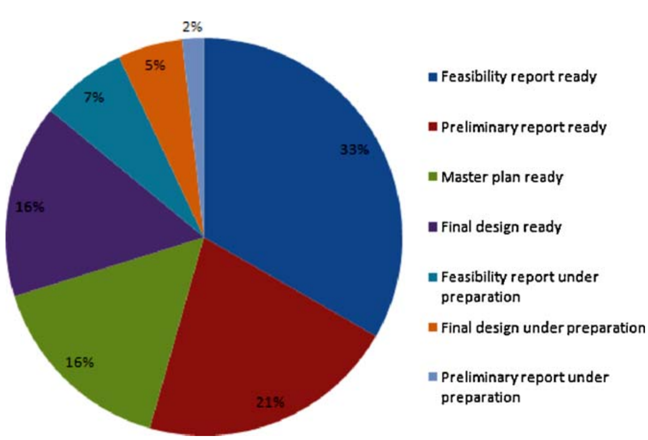

Fig. 4. Distribution of Turkey hydro power potential according to design level.

will account for 22% of the country's economically viable hydroelectric power potential, 118 billion kW. By 1998 June 15, the Ataturk and Karakaya dams, the most important investments of the GAP, had generated almost 135 billion kWh energy [28]. The hydropower plants completed in the frame of GAP projects are as given in Table 6 [24].

Ataturk dam is the biggest of Turkey and the sixth biggest of the world. The water level in Ataturk dam has fallen to 526.6 m, only 60 cm above the minimum level at which power production is possible, said a senior energy official, who requested anonymity. The power production in the Ataturk and Keban dams, along with two other dams in the area, amounts to some 42% of Turkey's hydroelectric power production and some 13% of its total power production. A summary of Turkey's major existing hydroelectric power plants is shown in Table 7.

However, many of these planned dams, such as the 1.200 MW Ilisu Dam, are controversial because of the large amount of land that would be flooded and the large number of people that would be displaced. A summary of the major hydroelectric power plants that are planned and under construction is shown in Table 8.

Turkey total hydropower capacity is estimated at 440 TWh per year. Some of this potential can be achieved with small hydroelectric plants (SHEPs) having individual capacities of 10 MW or less. It is estimated that, theoretically, Turkey has SHEP resources of 710 GW for project generation and 300 MW for total installed capacity [30]. SHEP development in Turkey was initiated in 1900. Since then, municipalities in rural areas have installed many decentralized plants by private entrepreneurs, and by some government organizations. Temelsu is a well-known Turkish consulting engineering company, which provides multi-disciplinary engineering services, locally and internationally, since its foundation in 1969. It is estimated that, Turkey has SHEP resources of 710 GW for project generation and 300 MW for total installed capacity. Annual increases of SHEP capacity during the past 25 years average 8–12% [30,31].

Table 6
The hydropower plants completed in the frame of GAP projects.

Generating facility	River name	Generating capacity (GWh)
Ataturk	Euphrates	8515
Karakaya	Euphrates	6386
Birecik	Euphrates	2384
Karkamis	Euphrates	670
Batman	Batman	702
Dicle	Tigris	390
Kralkizi	Tigris	336

Table 7
Hydroelectric generating plants in Turkey (20 MWe and larger) [29].

Generating facility	Owner	Location		Capacity (MWe)
		Province	River	
Adiguzel	DSI	Denizli	Buyuk Menderes	62
Almus	DSI	Tokat	Yesilirmak	27
Altinkaya	DSI	Samsun	Kizilirmak	700
Aslantas	DSI	Adana	Ceyhan	138
Ataturk	DSI	Sanliurfa	Euphrates	2400
Batman	DSI	Batman	Batman	198
Berke	CEAS	Adana	Ceyhan	515
Birecik	Birecik AS.	Sanliurfa	Euphrates	672
Camlica-I	n/a	n/a	n/a	98
Camligoze	DSI	Sivas	Kelkit	33
Catalan	DSI	Adana	Seyhan	169
Demirkopru	DSI	Manisa	Gediz	69
Derbent	DSI	Samsun	Kizilirmak	58
Dicle	DSI	Diyarbakir	Tigris	110
Gezende	DSI	Icel	Ermenek	159
Gokcekaya	DSI	Eskisehir	Sakarya	278
Hasanugurlu	DSI	Samsun	Yesilirmak	500
Hazar I &II	Etibank	n/a	n/a	30
Hirfanli	DSI	Kirsehir	Kizilirmak	128
Kadincik I & II	CEAS	n/a	n/a	126
Kapulukaya	DSI	Kırıkkale	Kizilirmak	54
Karacaoren I	DSI	Burdur	Aksu	32
Karacaoren II	Kepez AS.	Burdur	Aksu	47
Karakaya	DSI	Diyarbakir	Euphrates	1800
Karkamis	DSI	Kahramanmaras	Euphrates	189
Keban	DSI	Elazig	Euphrates	1330
Kemer	DSI	Aydin	Akcay	48
Kepez I & II	Kepez AS.	Antalya	Dudencay	32
Kesikkopru	DSI	Ankara	Kizilırmak	76
Kilickaya	DSI	Sivas	Kelkit	124
Kokluce	n/a	n/a	n/a	90
Kovada II	DSI	Isparta	Kocabey	51
Kralkizi	DSI	Batman	Tigris	94
Kuzgun	DSI	Erzurum	Serceme	23
Manavgat	Kepez AS.	Antalya	Manavgat	48
Menzelet	DSI	Kahramanmaras	Ceyhan	124
Oymapinar	DSI	Antalya	Manavgat	540
Ozluce	DSI	Bingol	Peri	170
Sariyar	Etibank	Ankara	Sakarya	160
Seyhan	DSI	Adana	Seyhan	59
Sir	CEAS	Kahramanmaras	Ceyhan	284
Suatugurlu	DSI	Samsun	Kizilirmak	76
Tortum	Iller Bank	Erzurum	Tortum	26
Yenice	DSI	Eskisehir	Sakarya	38

n/a: Not available

4. Review of wind–hydro pump storage systems

Wind power production introduces more uncertainty in operating a power system: it is variable and partly unpredictable. To meet this challenge, there will be need for more flexibility in the power system. While wind energy sources cannot provide energy on demand independently, they can be used together to form the pumped storage system and meet demands collectively. In this simple system of water reservoirs, generators and turbine and wind turbines are used to harness kinetic energy from the wind to power water pumps, transferring water from a lover altitude to a reservoir at a higher altitude. By filling this higher reservoir, the pumped storage system effectively creates from hydropower where electricity is stored during hours of low demand, via pumping water between reservoirs at differing altitudes. On the other hand, wind-hydro pumped storage systems is a method of storing and producing electricity to supply high peak demands. At times of low electrical demand, excess electrical capacity is used to pump water into an elevated reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine, generating hydroelectricity. Reversible turbine/generator assemblies act as pump and turbine. Between 70% and 85% of the electrical energy used to pump the water into the elevated reservoir can be regained in this process. Model of wind-hydro pump storage systems is seen in Fig. 5.

This system is economical as it flattens out the variations in the load on the power grid, permitting thermal power stations such as coal-fired plants and nuclear power plants that provide base-load electricity to continue operating at their most efficient capacity, while reducing the need to build special power plants which run only at peak demand times using more costly generation methods. As well as energy management, pumped storage systems are important components in controlling electrical network frequency and in provision of reserve generation. Thermal plants are much less able to respond to sudden changes in electrical demand, which cause frequency and voltage instability. Pumped storage plants, in common with other hydroelectric plants, can respond to these changes within seconds. The response of sudden changes for some power plants is seen in Table 9.

A major advantage of combining pumped storage with other sources is cost saving. Instead of having another plant provide energy during the peak demand hours, you can utilize the stored energy to provide the power. No fossil fuels are burned for this system, nor are there any pollutants released into the atmosphere, providing yet another to the system.

4.1. Potential, use and current situation of pumped storage plants

When installed hydraulic energy capacity of the countries, having much highland by means of topographic structure, is examined, it can be seen that approximately 50% of their installed capacity consists of reservoir or pumped storage plants. Likewise, Reservoir and pumped storage plants constitute approximately 30% of installed capacity in the countries having many hilly fields.

While reservoir hydroelectric power plants produce 1000–3000 h in full load operation time per year, this value is between 4000 and 5000 in stream hydroelectric power plants. As a result, the share of total hydroelectric production of reservoir or pumped storage plants varies between 5% and 28% as seen in Table 10.

Potential storage capacity can be divided in to two categories one of which is long term storage and the other one is short term storage. While short term storage consists of a time period between 1 and 24 h, long term storage expresses one day or more time. The distribution of worldwide hydroelectric technical capacity according to plant types is shown in Table 11 [33].

4.2. Development process of pumped storage hydroelectric power plants

Pumped storage hydroelectric power plants, firstly used in Italy and Switzerland in1890, were built with commercial purposes in Europe at the beginning of 1930s. Although the actual development started after the Second World War. In the last decade, especially with the liberalization of electric industry in Europe, basic investment decisions in electric industry changed, and due to the high cost occurring in peak hours, this power plant gained more popularity.

In the studies of the first Energy Council in 1998 made in Turkey, it is stated that construction of the pump storage power plants near the consumption locations and having sufficient capacity determined by results of feasibility studies made since 2006 in order to meet peak power demand in Turkey, is very important by means of the sufficiency and reliability of electric energy.

In 2001, it was switched to competitive free market in Turkey. Besides, since the development of the wind power plants being an important potential in the country, and other renewable energy

Table 8
Hydroelectric generating plants in Turkey (planned or under construction) [29].

Generating facility	Owner	Location		Capacity (MWe)
		Province	River	
Alpaslan II*	Earth Tech; ABB (and others)	Mus	Murat	200 P
Artvin	DSI	Artvin	Coruh	320 P
Aslancik	n/a	Giresun	Harsit	90 P
Boreka	DSI	n/a	Coruh	300 P
Boyabat	Kepez AS	Sinop	Kizilirmak	510 C
Camlihemsin	DSI	n/a	n/a	180 P
Cizre	DSI	Mardin	Tigris	240 P
Deriner	DSI	Trabzon	Coruh	670 C
Durak*	Harza; Clark; ABB (and others)	Rize	Durak	120 P
Eric*	Black & Veatch (and others)	Erzincan	Karasu	170 P
Garzan	DSI	Diyarbakir	Garzan	90 P
Gursogut*	Lemna Int'l (and others)	Eskisehir	Sakarya	242 P
Hakkari*	Raytheon; ABB (and others)	Hakkari	Zap	208 P
Ilisu	DSI	Batman	Tigris	1200 P
Karg*	Black & Veatch (and others)	Eskisehir	Sakarya	194 P
Kayser	DSI	Diyarbakir	Tigris	90 P
Konaktepe I & II*	Stone & Webster (and others)	Tunceli	Munzur	138 C
Kopru	DSI	n/a	Kopru	189 P
Munzur	n/a	n/a	Munzur	235 P
Mut*	Morrison Knudsen ABB	Icel	Goksu	91 P
Pervari*	Parsons; ICF Kaiser	Siirt	Boten	192 P
Silvan	DSI	Diyarbakir	Tigris	150 P
Torul	DSI	Gumushane	Harsit	122 C
Yamula	n/a	Kayseri	Kızılırmak	150 P
Yedigoze	DSI	n/a	Seyhan	300 P
Yusufeli	DSI	Artvin	Coruh	540 P

sources, and in order to provide their optimal use, the significance of these kinds of power plants is rapidly increasing. However, pumped storage power plants were stated neither in the projections Energy and Natural Sources Ministry performed, nor in the ninth seven years development plan [32]. Besides, in final declarations of the 10th energy congress, it was stated that in meeting maximum load demand in electric energy, pumped storage power plants should have been implemented [34].

In 2001, the importance of pumped storage power plants has increased even more for developing of wind plants having important potential and other renewable energy resources and for providing their optimum usage and for being transmitted http://www.tureng.com/search/rekabet%C3%A7icompetitive free market model in Turkey. Pumped storage plants are not mentioned neither Ministry of Energy and Natural Resources projections nor ninth seven year development plan [32].

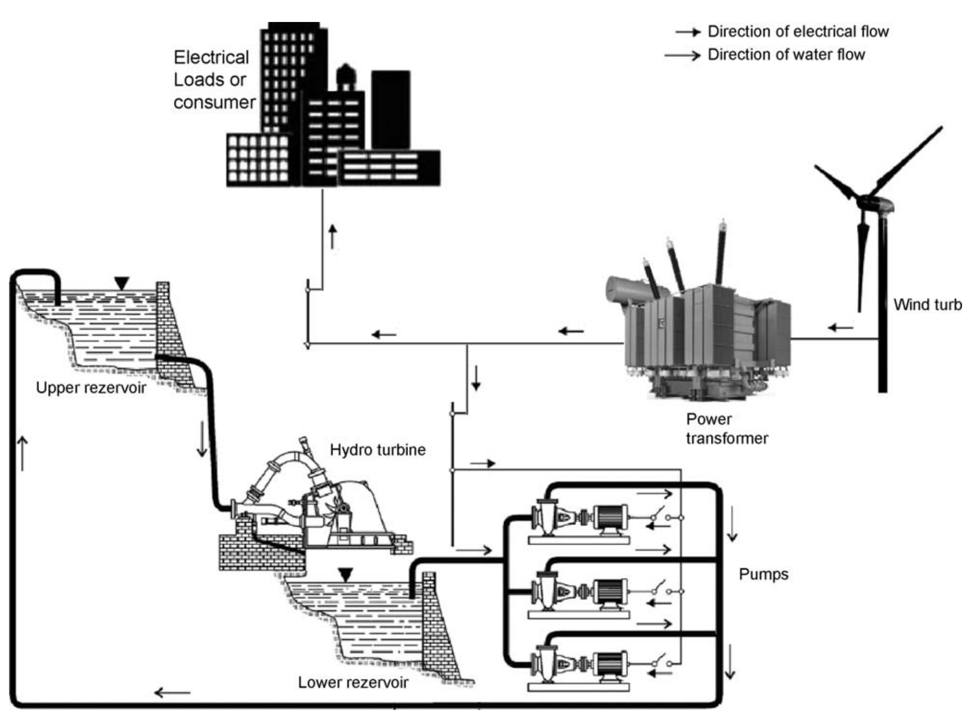

Fig. 5. Model of wind-hydro pump storage systems.

Table 9
The response of sudden changes for some power plants [32].

Type of projects	The response time of sudden changes
Classical hydropower plants	3–5 min
Pumped storage hydropower plants	3–5 min
Fuel Oil plants	3 h
LNG-Natural gas plants	3 h
LNG Combine plants	1 h
Coal fired plants	4 h
Nuclear plants	5 day

4.3. Completed studies concerned with pumped storage hydroelectric power plants

There are a lot of studies on wind-hydro pumped storage systems. Many researchers have examined wind-hydro pumped storage systems from different points of view [35–48]. Some of these researchers are interested in optimization of wind-hydro pumped storage systems [35–40], and the others are interested in modeling and analysis of wind-hydro pumped storage systems [41–48].

Cristorafi et al. defined another methodology in order to indicate relationship between cost optimization and magnitude of the combined wind turbine and pumped hydro system using real wind and load data [35]. Guan et al. [36] proposed an optimization based method for operation of hydro-thermal system with time and program by using Lagrange approach method. In this paper it is concentrated on solution methodology for pumped storage units. Pumped storage units can be operated in production, pumping and no load [36]. Katsaprakakis et al. [37] proposed a power production system for Astypalaia Island. Astypalaia, a small island in Aegean Sea, is not connected to interconnected grid. Energy production is only based on autonomous thermoelectric plant. In 2003, maximum annual load demand of the island was more than 1.78 MW and energy production cost was more than 0.20Euro/kWh. In the suggested system, it is aimed to benefit maximum from wind energy and deduct the use of imported fossil fuel consumed in the production of electrical energy to minimum value [37]. Bakos [38] made a study about the operation of a hybrid wind-hydro power system to produce low cost electricity. A specific implementation was made for Ikeria Island in Greece and results were presented [38]. Castronuovo and Lopes [39] proposed a methodology for combined wind power production and hydro storage system. The increasing trend of the concept of combined use of wind power production and hydro storage system engendered the application of operational optimization approach [39]. Castronuovo and Lopes [40] proposed the use of water storage availability both to reduce the active power output variation resulting from the in continuity of wind energy source, and to get economic income while operating the wind farm. An hourly discretized optimization algorithm was proposed [40].

Kaldellis [41] proposed wind-hydro electric production system to meet electricity demand of Aegean islands. He implemented parametric analysis of the system to meet the demand of the islands having rather good local wind potential [41]. Kaldellis and Kavadias [42] developed a model qua solution proposal in order to remove the lack of water and meet energy demand of Aegean islands. Since the islands have rather good wind potential, it was aimed to remove electric cut off and the lack of clean water by building wind hydro combined energy production station. In this study, it is thought that even if the potential of wind is good, it may not always meet the energy demand individually, therefore this model is asserted. Hence Kaldellis and Kavadias developed a methodology for optimal wind-hydro solution and implemented this methodology to Aegean islands. Real data are used in numeric calculations, long term wing speed measurements, and demanded electric loads and operating characteristics of system components [42]. A simulation model in order to evaluate benefits of operation of Tianhuangping pumped storage hydro power plant in Shanghai electric grid was presented by Wei He. In Tianhuangping pumped storage hydro power plant average coal consumption decreased

Table 10
Worldwide hydroelectric storage potentials [33].

	Technical potential of hydroelectric production (TWh/year)	Technical potential of hydroelectric capacity (GW)	Technical potential of hydro storage production (TWh/year)	Technical potential of hydro storage capacity (GW)
Africa	1,750	515	205	206
Asia (including Russia and Turkey)	6,700	2,762	784	1,105
Avustralasia (Australia New Kaledonya, New Zealand, Solomon Islands, Vanatu and Papua Newgine including Newgine	270	86	32	35
Europe (excluding Russia and Turkey)	1,225	375	143	150
Northern & Central America	1,657	344	194	138
Southern America	2,720	543	318	217
World	14,320	3,635	1,675	1,454

Table 11
Distribution of worldwide hydroelectric technical capacity according to plant types.

	Technical potential of hydroelectric capacity (GW)	Technical potential of river capacity (GW)	Technical potential of short term hydro storage capacity (GW)	Technical potential of long term hydro storage capacity (GW)
Africa	515	309	144	62
Asia (including Russia and Turkey)	2,762	1,657	784	1,105
Australasia (Australia New Caledonia, New Zealand, Solomon Islands, Vanatu and Papua Newgine including Newgine	86	52	32	35
Europe (excluding Russia and Turkey)	375	225	143	150
Northern & Central America	344	207	194	138
Southern America	543	326	318	217
World	3,635	2,181	1,675	1,454

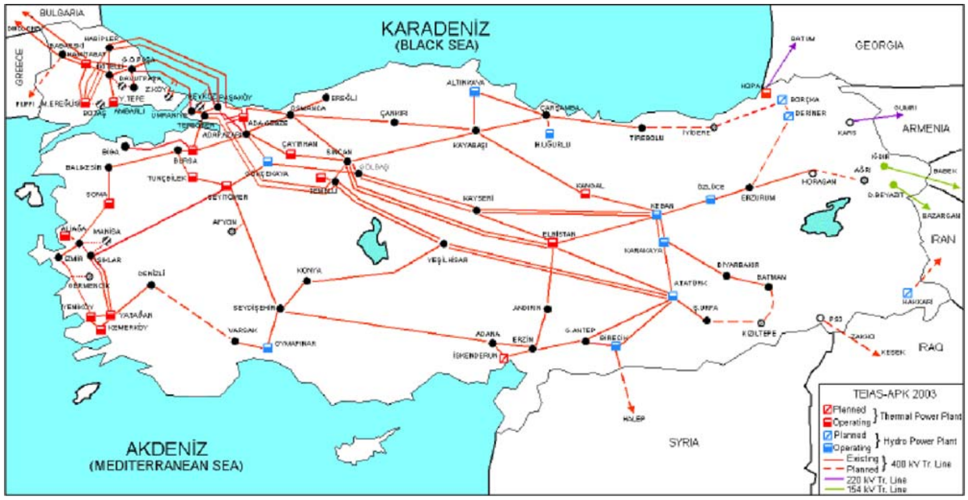

Fig. 6. 380 kV power transmission system of Turkey.

5.1 g/kWh and an additional peak capacity of 600 MW for Shanghai electric grid was achieved [43]. Sohrabi proposed a dynamic model for the evaluation of a pumped storage project. In this model, optimal growth policy was determined, and based on this model, it was seen that rodbar pumped storage system is more economic when different alternative systems are evaluated together [44]. Hosseini et al. [45] were concentrated on a method in that paper. A computer program for energy calculation was developed to estimate the most significant indices of hydroelectric power plant by using sensitivity analysis method [45]. Nanahara and Takimoto [46] defined a methodology to determine the size of the reservoir in pumped storage systems. In that paper, by considering the indefinite of source and demand capacity and cooperation of pumped storage system both daily and weekly, Monte Carlo simulation method was presented. When the method is handled in the aspect of system reliability, required reservoir capacity was determined. Load profile and the sensitivity of the reservoir length for the production were examined on a case study [46]. Anagnostopoulos and Papantonis [47] performed the design of pump unit in hybrid wind-hydro power plant and quantative analysis of optimum size. The aim is to reduce the quantity of the energy produced from wind which can not be converted to hydraulic energy as a result of the pump power operation restraints and small interval operation [47]. Kaldellis et al. [48] investigated the probability of combined wind-hydro energy plant in Archipelago, a middle sized island in Aegean Sea. Real time measurements and obtained calculation results based on experimental data proves the validity of the proposed solution [48].

4.4. The role of wind-hydro pumped storage systems in Turkey

Turkish economy has been increasing about 7–10% since 2000. Economic growth caused concentration to natural gas power plants to meet electrical energy demand. Because Turkey has not enough natural gas resources, imported the required natural gas.

Due to the fact that Turkey is more suitable countries by means of wind and hydropower potential more than many European countries, Turkey must use wind and hydropower instead of natural gas and it is an essential that Turkey's energy demand is provided by renewable energy resources. Central Black Sea coast is the most suitable region to built wind-hydro pumped storage systems due to the mountains lie parallel to the coast, black sea region is rainy all seasons and it is the rainiest region in the whole of Turkey, it is one of the richest regions from the aspect of rivers. The longest river of Turkey is Kizilirmak where is located at central Black Sea. Therefore, black sea region is more suitable for pump storage system applications. Although there are a lot of small hydropower plants in this region, these small hydropower plants do not use with the aim of pumped storage systems.

Energy transmitted from Turkey's 380 kV power transmission system is shown in Fig. 6. More power is transmitted with longer transmission lines by widespread use of hydroelectric power plants. There are three main hydroelectric power plants called Keban, Atatürk and Karakaya in Turkey's transmission system shown in Fig. 6 at point A. Generated power is transmitted via series capacitor to load centers located in west side of the country in Fig. 6 at point B. In 2006 maximum power is measured as 27,664.4 MW and minimum power was measured as 13700.6 MW which means %50 load variations during a year. Power system peak load is provided by big hydro power plants. After using pump storage systems transmission losses will be reduced.

5. Conclusions

In view of the uncertain future concerning the fuel worldwide reserves and the continuous deterioration of the environment, a progressive interest in the wind energy applications is taking place in all European countries. The future need advanced pumped storage facilities to accommodate the growing penetration of wind energy. Wind/hydro solutions not only guarantees the continuous capability to cover the electricity demand of local grid, but minimizes the dependency on imported fuel and also reduces the negative resulting from the usage of fossil fuels.

Note that the energy storage need not be located at the wind farm or its designated load, but it must be served with adequate transmission capacity. We found that the application of storage for providing standing reserve could significantly reduce the amount of wind curtailed and reduce the amount of energy produced by conventional plant. This was particularly prominent in generating systems with limited flexibility.

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